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SCALABILITY OF CONCRETE CONTAINERS UNDER IMPACT LOADS

Report No. 88-301-K

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ABSTRACT

This report summarizes the findings of a series of investigations into the use of scale model testing for licensing of concrete shielded casks for transportation of irradiated nuclear fuel. These included an extensive literature review and two series of tests on scaled models that represented features of the Concrete Integrated Cask (CIC) being developed for fuel storage and transport. The investigations demonstrated that scale models can provide reliable predictions of structural response to impact load for containers with steel skin enclosing the concrete. It was also demonstrated that the impact loads scale very well when the models are close scale replicas and when the conditions of impact (model orientation and drop height) are identical.

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SCALABILITY OF CONCRETE CONTAINERS UNDER IMPACT LOADS

J.D. Tulk

1. INTRODUCTION

The application to license the Concrete Integrated Cask (CIC) for off-site transportation will be supported by tests to demonstrate that the package can withstand impact (drop test) and thermal (fire test) loads. As the very large size of the complete CIC package makes it impractical to carry out tests at full scale, Ontario Hydro intends to use tests on highly detailed half-scale models. The ATOMIC ENERGY CONTROL ACT SOR/83-740 Transportation Packaging of Radioactive Materials Regulations authorizes the use of "... tests with appropriately scaled models or specimens incorporating all significant features providing such tests are suitable for design purposes and test parameters have been suitably adjusted" (Schedule II, Part IV, paragraph 1(b)). The purpose of this paper is to discuss the requirements for "appropriate" scaling and to establish how test parameters are to be adjusted to ensure that scale model tests will provide reliable predictions of full scale behaviour.

This paper examines the basis for scaling theory and shows, with reference to experimental results, that concrete models of different scales provide very consistent results under impact conditions.

2. SCALING THEORY

2.1 Fundamental Concepts

Scaling theory provides the basis for a set of "scaling laws" which relate the behaviour of a scale model to that of a full scale prototype. If all scaling laws can be satisfied, then the model can be expected to mimic the full sized structure exactly.

The theory of scale model testing is based on dimensional analysis and Buckingham's Π (Pi) theorem. (See References /1,2,3,4/ for further discussion of this subject). Briefly, dimensional analysis shows that if the response of a structure can be described as a function of a finite number of variables, then it is possible to write a logically equivalent description based on a limited number of non-dimensional parameters or ratios. For example, if a deformation (d) of a structure is a function of the the velocity of impact (V), acceleration during impact (a), length (l), Young's modulus and density of the material (E and ρ) and time (t), then we can write:

$$d = f(V,a,l,E,\rho,t)$$

A logically equivalent expression of this relationship is:

$$d/l = F(\pi_1,\pi_2,\pi_3)$$

where:

$$\pi_1 = \frac{al}{V^2}$$

$$\pi_2 = \frac{Vt}{l}$$

and $$\pi_3 = \frac{V}{\sqrt{E/\rho}}$$

The π terms are all non-dimensional parameters.

The original expression had variables that depended on the size of the structure. However, the non-dimensional variables in the second version have no absolute scale associated with them. Since these relationships are logically equivalent, it follows that a scale model of the system would have identical (scaled) response, provided *all non-dimensional parameters are identical in the scale model and prototype.*

Scaling laws follow directly from the requirement to keep π terms equal in the prototype and model. If we use the subscripts "p" to denote the prototype (full scale version) and "m" to denote the model, then for a scale replica:

$$S = l_m/l_p$$

where S is the scale factor.

If the same material is used in the model and prototype, then:

$$E_m = E_p$$

and $$\rho_m = \rho_p$$

Keeping π_3 the same for model and prototype means:

$$V_m = V_p.$$

Now, to keep π_2 constant,

$$t_m = S.t_p.$$

This is an important relationship because it means that time will be compressed in a test with a reduced scale model. Impact durations will be reduced and the natural frequency of vibration increased.

To keep π_1 constant, it is necessary to have:

$$a_m = a_p/S$$

which means that accelerations will be higher in the model than in the prototype.

Finally, if the three π terms are stay constant over a change of scale, it follows that:

$$d_m = S.d_p$$

That is, deformations will be in scale.

This demonstration involves only a few variables. However, the same principle could be applied to a much more elaborate description of structural behaviour. In general, as more variables are included to describe structural geometry, material properties or other influences, it will be necessary to introduce more π terms and to work out more scaling laws. However, the basic procedure is the same as has been described here.

2.2 Applying Scaling Theory

The previous section outlined a method for defining a set of scaling laws which, if completely satisfied, would guarantee that the behaviour of a scale model exactly mimics the behaviour of the prototype. Unfortunately, it is seldom possible to perfectly satisfy all of these laws in the same experiment. Violations of the scaling laws may be due to the impossibility of keeping all of the π terms constant over a scale change or for practical reasons related to model building.

If the same material is used in the model as in the prototype, then most of the π terms that deal with material properties will automatically stay constant over a change of scale. However, because impact duration changes with a change in scale, mechanical properties that depend on strain rate will change to some degree. Scale models may also give inaccurate results when there is fracture in tension or shear. This is because the stress concentration that drives fracture depends on absolute (not scale) crack size.

Another set of issues arises because of manufacturing processes. Thin gauge steel sheet and wire is commonly cold worked from thicker material, and tends to have higher yield strength. It may be difficult to find sheet metal with exactly the correct thickness or bolts with thread sizes and pitches that are exact scale replicas of the prototype fasteners. For concrete structures, scaling requires the use of fine grades of aggregate which might cause subtle changes in the effective strength of the material.

The implication of all this is that scale model testing usually involves some compromise and approximation. However, it must be emphasized that the non-scaling factors - such as strain rate sensitivity and material granualarity - typically have minor effect on structural response for engineering materials at moderate scaling ratios.

For the CIC experiments, non-scaling will be minimized through use of a moderate scaling ratio, careful materials selection and precise model construction. A number of tests have been carried out to demonstrate that the structural response to impact loads is consistant, both qualitatively and quantitatively for models that resemble the CIC. These tests are described in the following section.

3. EXPERIMENTS WITH CONCRETE MODELS

3.1 Literature Review

A literature review conducted by the Ontario Hydro Civil Research Department examined the application of scale model testing to concrete models and reported the results of experiments that involved impact loading on concrete structures. The results of this study are reported in Reference /5/. This study noted that scaling of damage in concrete involves a degree of compromise because of the large number of variables (including surface and volumetric effects, cement paste and aggregate properties, water content, steel properties etc.). However, several experimental programs reviewed in the study reported good correlation between small and large scale test results for scaling ratios as large as 6:1.

3.2 Ontario Hydro Concrete Scaling Experiments

Research has been carried out by Ontario Hydro to demonstrate the the effects of scale on concrete structures similar in overall configuration to the Concrete Integrated Cask. This study had two main phases:

i) A series of drop tests with simple ring-shaped reinforced concrete structures; and
ii) A series of drop tests with steel-sheathed reinforced concrete models geometrically similar to the CIC.

3.2.1 Ring Model Experiments

The test models for this stage were four reinforced concrete rings (Figures 1, 2 and 3). The largest had an outer diameter of 1 m, an inner diameter of 600 mm and a length of 529 mm. The others were smaller, by scaling ratios of 0.81, 0.59 and 0.25 (Table 3.1). The models were all dropped on their side from a height of 4.5 m onto thick steel plates (Figure 4). Instrumentation included accelerometers, strain gauges and a high-speed movie camera. Details of the test procedures and results are contained in Reference /6/.

Table 3.1 Ring Model As-Built Dimensions

Model	Scale Ratio	Outer Diameter mm	Inner Diameter mm	Wall Thickness mm	Length mm	Mass kg
1	1.0	1000	600	199	529	695.8
2	0.81	825	495	165	430	377.8
3	0.57	575	345	116	305	128.8
4	0.25	250	153	49	135	10.9

The ring shape was chosen because it provided an opportunity to examine scaling effects for five potential types of damage in reinforced concrete (Figure 5):

- concrete crushing at the point of impact;
- cracking due to tensile bending stresses;
- crushing due to compressive bending stresses;
- shear cracking across the section; and
- spalling (cracking and separation) of unreinforced "cover" concrete.

Post test evaluation of the test samples included assessment of the degree of damage that occurred for each model, plus measurement of the permanent deformation (ovalization and crushing).

The test results showed that permanent ovalling deformations (out of roundness) scaled extremely well (Table 3.2). Patterns of local deformation were very consistent for all scales (Figures 6, 7). However, an obvious damage mode - loss of the unreinforced "cover" concrete - was more severe in the large models than in the small scale versions (Figure 8). Thus, while overall structural response showed good adherence to the the scaling laws, there were local effects that changed with the absolute size of the model. The most important deviation from scaling similitude involved fracture of unrestrained concrete. This is not expected to be significant for the CIC where shielding concrete is completely contained in a steel shell.

Table 3.2 Ring Model Deformations

Model	Original Diameter mm	Permanent Ovalling			Footprint	
		Lateral mm	% Change	Vert. mm	% Change	Width mm
1	600	620	+3.3	588	-2.0	150
2	495	510	+3.0	485	-2.0	103
3	343	355	+2.9	338	-2.0	82
4	153	156	+2.0	150	-2.0	27

3.2.2 Container Model Tests

The second phase experiments were designed to provide data on concrete scaling with models and test conditions that more closely resembled the CIC configuration. The models for these tests were cylindrical in shape, closed at one end and with a bolted lid at the other. A steel skin enclosed the concrete. The external dimensions of the models was patterned on the dimensions of an early design for the CIC, although details such as the lifting trunnions and drainage ports were not reproduced. The reinforcing steel in the models had steel/concrete ratios similar to the CIC reference design, but with a simplified layout. Four models were manufactured: two were approximately one-quarter the size of a CIC and two were one-eighth size. Although the models differed from the CIC design, they were closely scaled replicas of each other. A complete description of the models is contained in Reference /7/.

Table 3.3 Container Model Dimensions

	Quarter Scale	Eighth Scale
Outside Diameter	653 mm	326.5 mm
Height	895 mm	447.5 mm
Inner Diameter	412 mm	206 mm
Cavity Depth	750 mm	375 mm
Lid Diameter	399 mm	200 mm
Lid Thickness	114 mm	57 mm
Outer Skin Thickness	2.657 mm	1.367 mm
Inner Skin Thickness	3.797 mm	1.897 mm
Main Re-bar diameter	9.9 mm	5.0 mm

3.2.2.1 Top Corner Drops With Impact Limiters

First stage testing of these models involved nine metre drops of complete package models (including impact limiters and a "payload" mass). Models fell onto a top corner and were aligned so that the centre of gravity was approximately above the point of impact (Figure 9). One "quarter scale" and two "eighth scale" models were tested. Test results are reported in Reference /8/.

These tests established several principles of importance to the CIC development program:

- Acceleration time histories measured on the cask models and on the payloads showed that the relative magnitude and duration of the impact decelerations (and hence impact loads) agree very closely with scaling theory (Figures 10 and 11).
- The type and extent of damage to the impact limiters was very consistent for both scales (Figure 12).
- There was no observable damage to the concrete container or lid in either size of model.

These results demonstrated that overall package behaviour was very consistent over a 2:1 scaling ratio. They also showed that damage to the concrete components can be minimized through good impact limiter design.

3.2.2.2 Top Corner Drop Tests with No Limiters

The first stage tests with the "container" models (ie, with impact limiters) showed that impact loads scaled very accurately. However, they did not provide direct evidence that damage to concrete would be reproduced in scale model tests, mainly because there was no discernible damage to the concrete components. Obviously a good transportation package design would avoid serious damage to the main containment vessel. However, we believe that it is important to establish that all possible failure modes in the full scale design would be reproduced in scale model tests. This required more severe tests.

The second series of tests was based on a top-corner impact without impact limiters. Two samples were tested, one nominal eighth-scale model and one quarter-scale. The drop height was 9 metres, but because of the direct impact between container and target, impact loads were much higher than in the previous set of tests.

Results of these tests showed that accelerations and impact duration scale well (Figures 13 and 14). In both models, the superficial damage consisted of an area of local crushing at the point of impact (Figures 15 and 16). The extent and depth of the crushed zone scaled closely (Table 3.4).

Table 3.4 Container Model Dimensions

	Quarter Scale	Eighth Scale
Crush Zone Length	370 mm	205 mm
Crush Zone Width	90 mm	52 mm

Following the tests, the damaged models were cut open to reveal the extent and nature of internal crushing and deformation. Figures 17 to 20 record the state of concrete in the crush zone and in surrounding regions. Observations are summarized below:

- Outer skin remained intact in both models, keeping concrete confined.
- In both models, concrete is heavily damaged in the immediate crush zone. This includes pulverization of cement matrix and splitting of pieces of aggregate.
- The extent of the crush zone was consistent with the scale of the models (Figures 19, 20).
- Although concrete in the crush zone is heavily damaged, it remained tightly packed. There were no voids or through-wall cracks.
- Concrete outside of the crush zone was sound, with no significant cracking.

3.2.2.3 Side Drop with Minimal Limiters

For the third set of tests, the containers were dropped on their sides (i.e. with their central axis parallel to the target plate). The impact limiters from the first phase tests were mounted on the containers. However, these limiters had been designed to protect the top corner drop and were too small to completely cushion the cask in the side-drop orientation. Thus impact limiters "bottomed out" and deceleration levels were much higher than for the original top corner tests. One quarter-scale model and one eighth-scale model were tested.

In spite of the higher "g" loading, there was no obvious damage to the containers beyond scuffing of the outer shell. There was no significant change in circularity of the cylinders. The test samples were cut open on a horizontal section approximately 50 mm and 100 mm below the top surface (see Figures 21, 22). There was no detectable cracking of the concrete in the 1/8 scale model and only fine cracks running circumferentially around the wall of the quarter-scale model (Figure 22).

4. BRITTLE FRACTURE

4.1 Linear Elastic Fracture Mechanics

Brittle fracture is a phenomenon whereby a crack, initiating at a relatively small flaw, can propagate rapidly through a structure/9/. According to the theory of linear elastic fracture mechanics, brittle crack propagation depends on the overall state of stress σ in the structure, the initial crack size "a" and the magnitude of a factor K_I (known as the "stress intensity factor") at the crack tip. These paramters are related through an equation of the form:

$$K_I = C\sigma \sqrt{\pi a}/Q$$

where C is a constant depending on the crack configuration and Q depends on crack shape. K_I has units of stress length ($MPa.m^{1/2}$).

A crack will grow in an unstable manner if:

$$K_I = K_{Ic}$$

where K_{Ic} is a property of the material.

From the point of view of scale modelling, it is important to note that crack propagation depends on the absolute size of the crack size "a". Thus, it would not be reasonable to reduce flaw or crack sizes in proportion to the model size. To this extent, brittle fracture in not directly scalable.

4.2 Fracture in the CIC

In practice, brittle fracture occurs when there is some combination of high stress, large flaws and low fracture toughness in the material. For the CIC design, brittle fracture of the steel components will be avoided by a combinations of design features:

- Stresses are limited to levels below the yield strength of the material through careful impact limiter design[1].
- The material selected for the skin will have good toughness properties down to $-40^{o}C$.
- Rigorous inspection at the time of manufacturing will limit flaw size.

If these measures can eliminate the possibiltiy of brittle fracture in the CIC, then there is no requirement to ensure that this phenomenon is fully scalable. The final Safety Analysis Report for the CIC will include an assessment of the potential for brittle fracture, based on stresses, material properties and maximum plausible flaws appropriate for full-scale containers. Measured values for fracture toughness of steel at $-40^{o}C$ will be explicitly included in the analysis.

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1. Stresses in the impact limiters themselves will be well above yield. However, these components are made of austenitic stainless steel which does not exhibit significant loss of toughness at low temperatures.

The possibility of brittle fracture of the steel reinforcing bar is limited because the diamter of the bars is small compared to the critical flaw size. The reinforcing steel is not welded, which elminates an important potential source of flaws that would serve as crack initiation sites.

There is potential for fracture-type damage to the concrete under tensile or shearing stress. The experiments with ring-shaped samples showed that tensile fracture of unreinforced concrete was more severe with larger scale models. This is consistent with the theoretical prediction that brittle fracture increases with absolute crack size. However, the tests with steel-clad container models showed that because of protection afforded by the impact limiters, and because of restraint offered by the reinforcing steel and outer shell, tensile or shear cracking in concrete is not a significant mode of failure for the Concrete Integrated Cask design.

5. CONCLUSIONS

We conclude that carefully detailed, moderately scaled models will provide reliable predictions of the structural response of concrete containers under impact loading. The theoretical relationships have been backed up by experimental evidence that showed a high degree of scalability over a 2:1 for a set of models similar to the CIC. The tests clearly demonstrate the following:

- Impact limiter behaviour was very consistent over a 2:1 scaling ratio.
- Crush zones on the heavily impacted top corners of the container models were found to be very consistent in terms of both extent and modes of deformation.
- Strain rates will be higher in small scale models because of the reduction in impact duration. However, there is no evidence from either the literature review or our tests that strain rate effects have a significant influence on concrete structures for a 2:1 scale change.

Brittle fracture is not directly scalable because of the dependency on absolute crack (flaw) size. However, through careful materials selection and inspection, it will be possible to avoid brittle fracture failures in the steel components.

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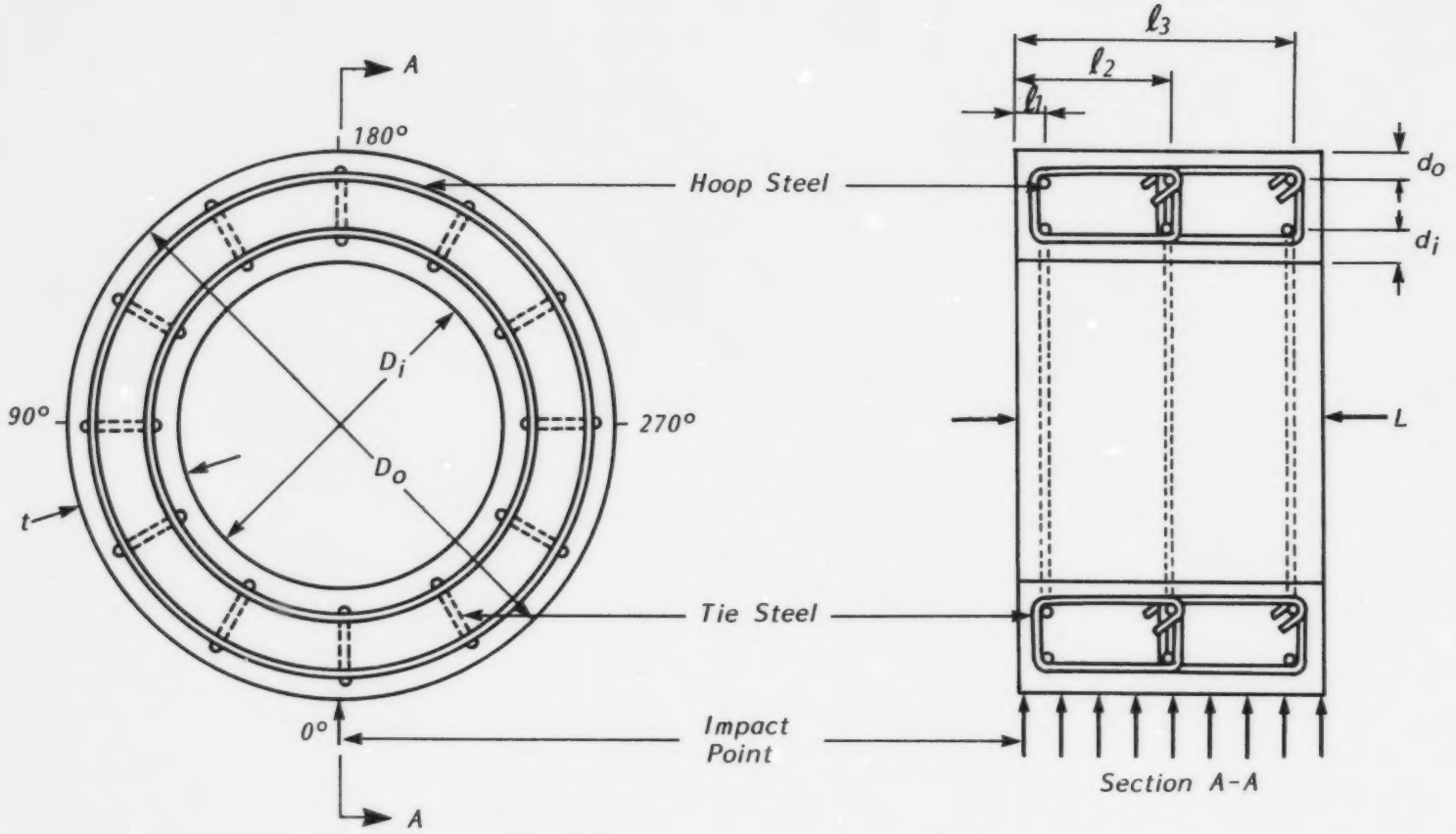

Notes: 1) *All steel dimensions are to the centreline of the hoop reinforcing bars.*
2) *Refer to Table 3.1 for the as-built dimensions of the specimens.*

FIGURE 1

SPECIMEN SHAPE AND REINFORCEMENT DETAILS

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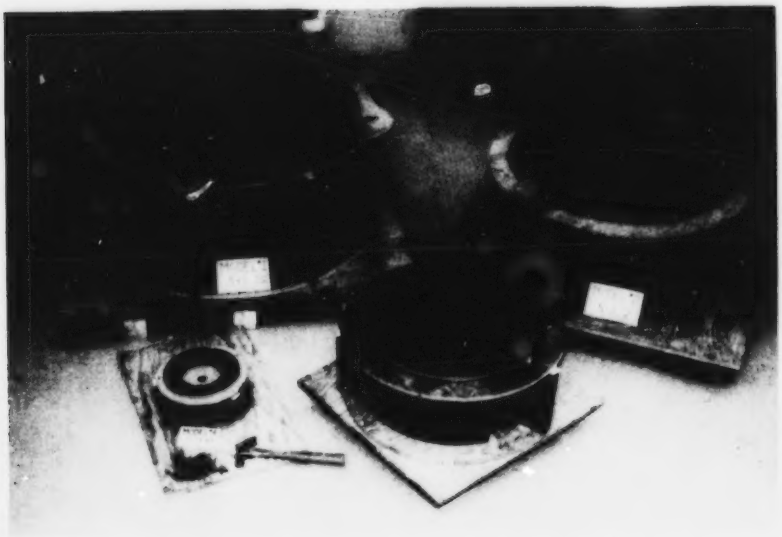

FIGURE 2
SPECIMEN FORMS

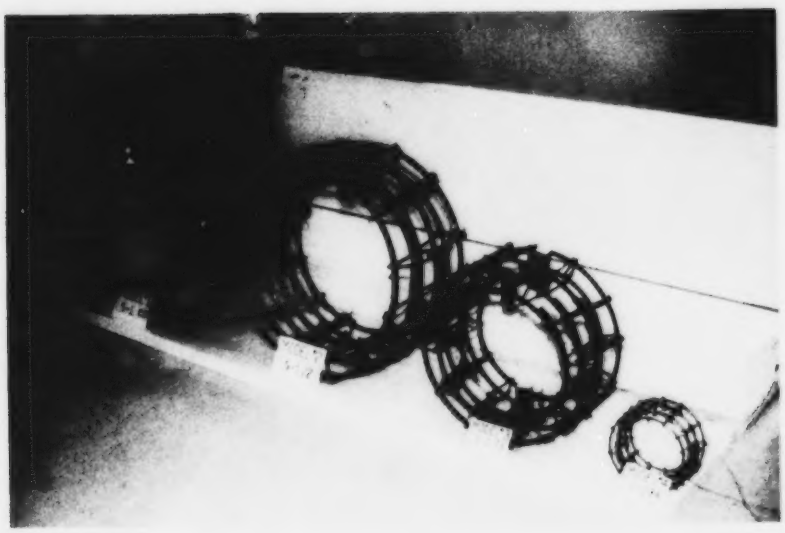

FIGURE 3
SPECIMEN REINFORCING CAGES

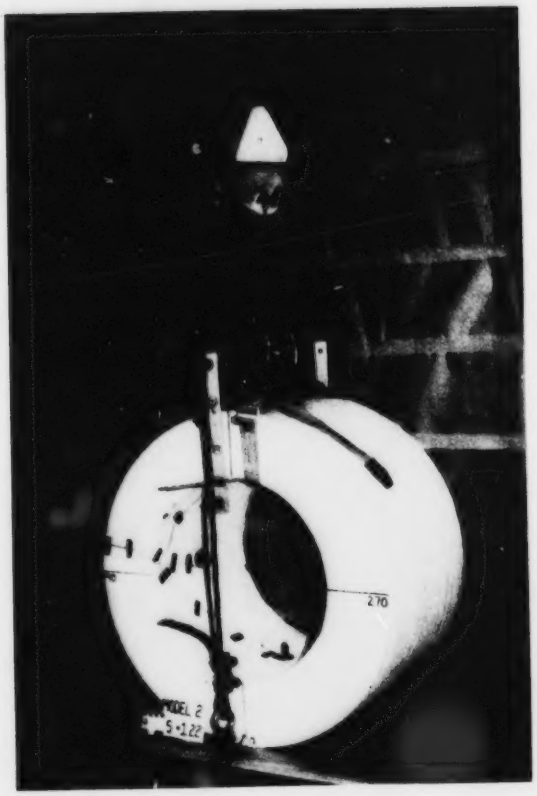

FIGURE 4

SPECIMEN TESTING ARRANGEMENT,
GUIDEWAY SYSTEM, AND RELEASE MECHANISM

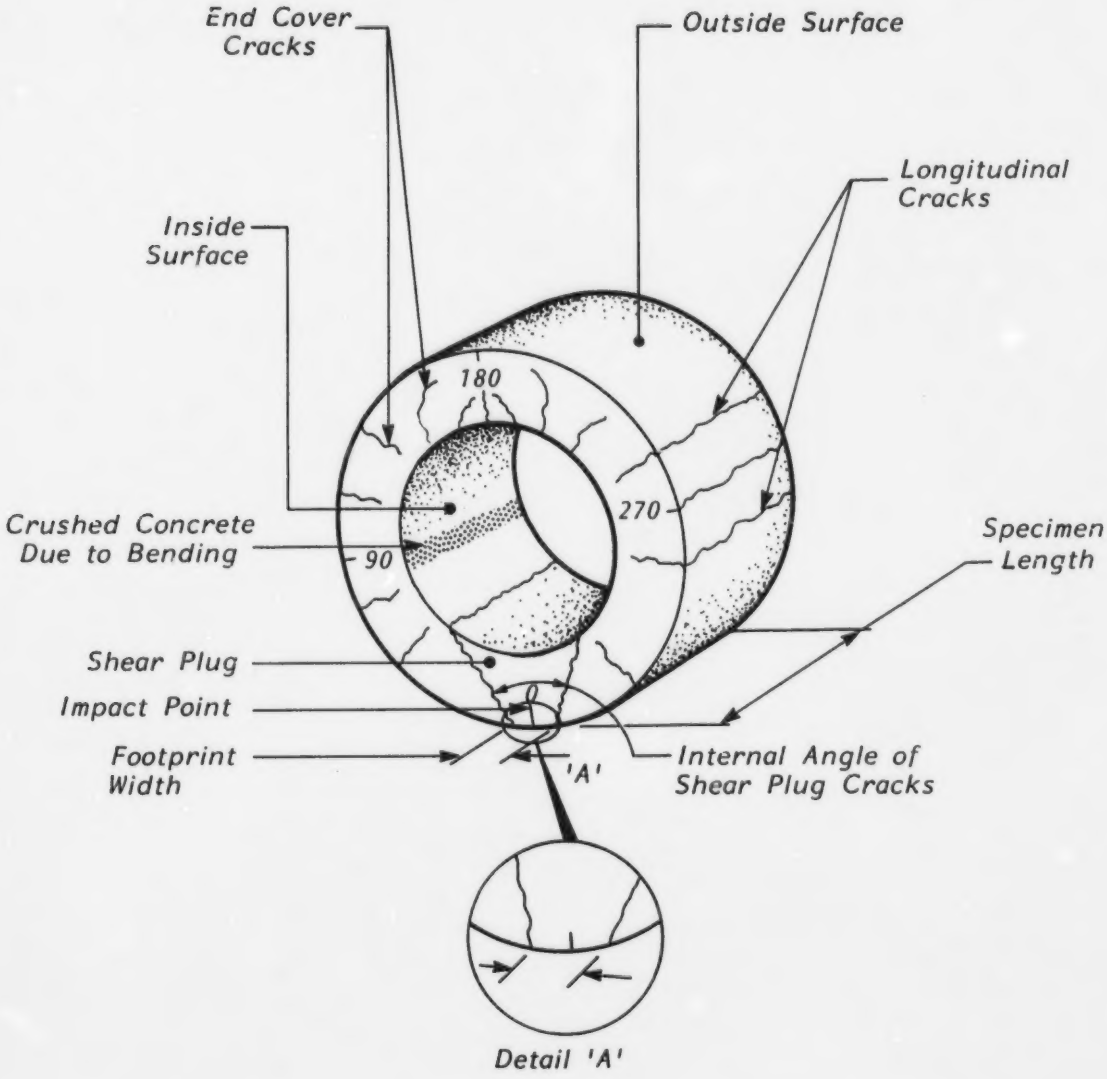

FIGURE 5

TYPICAL DAMAGE PATTERNS AND REFERENCE TERMS USED IN DESCRIPTION OF MODELS

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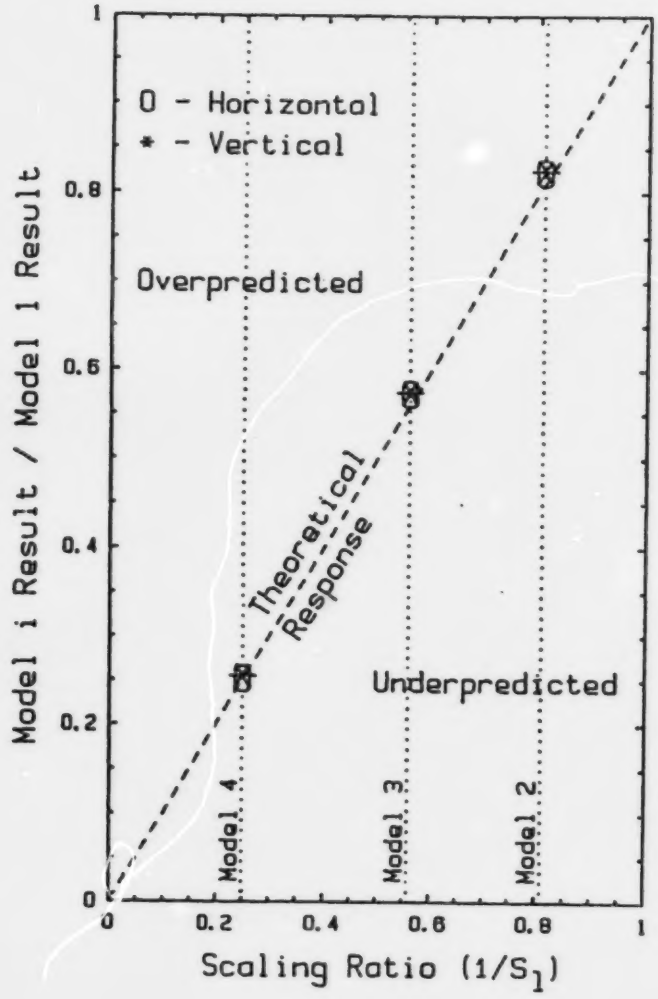


Figure 6
Permanent Ovalling

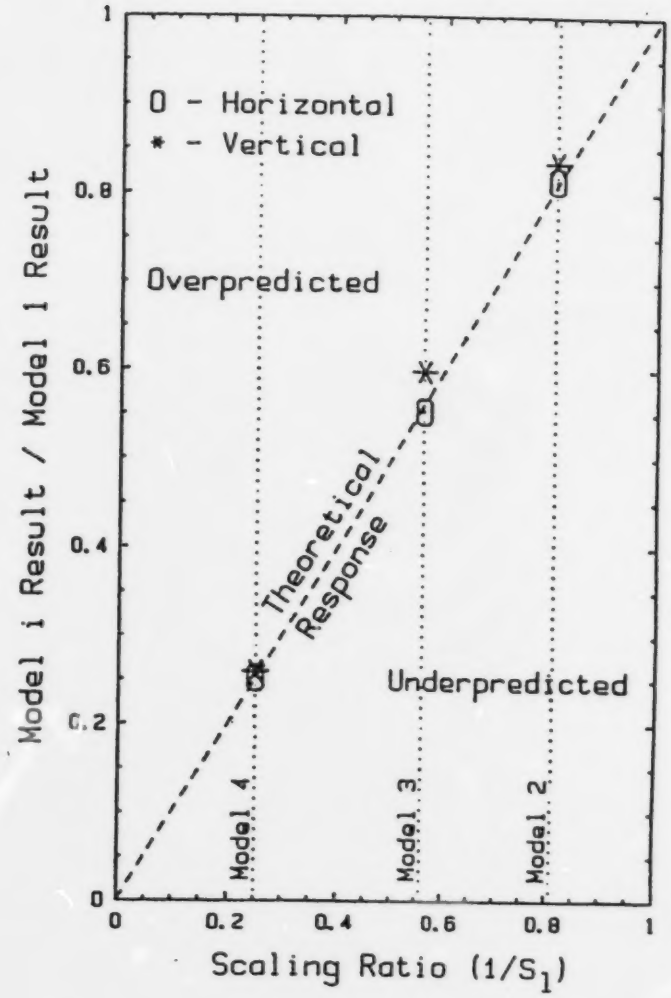
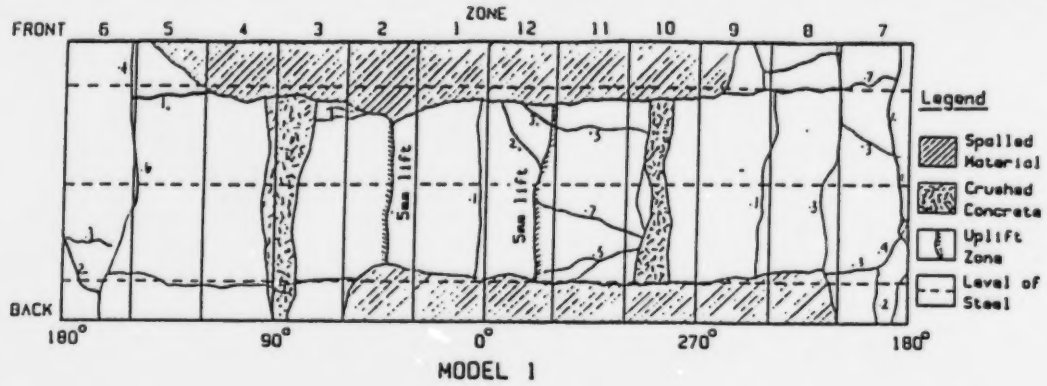
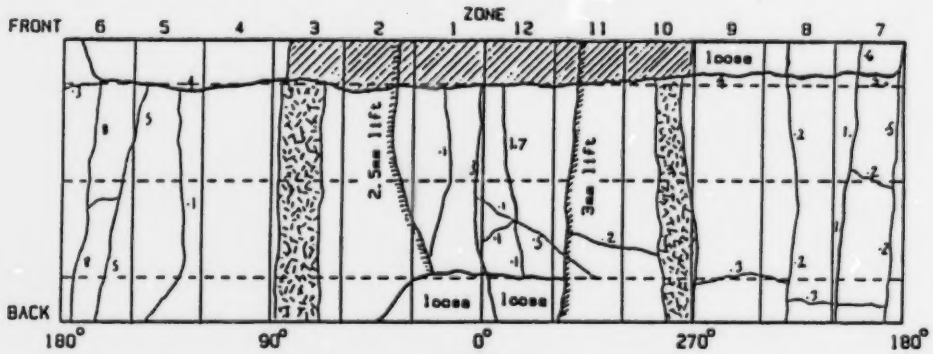


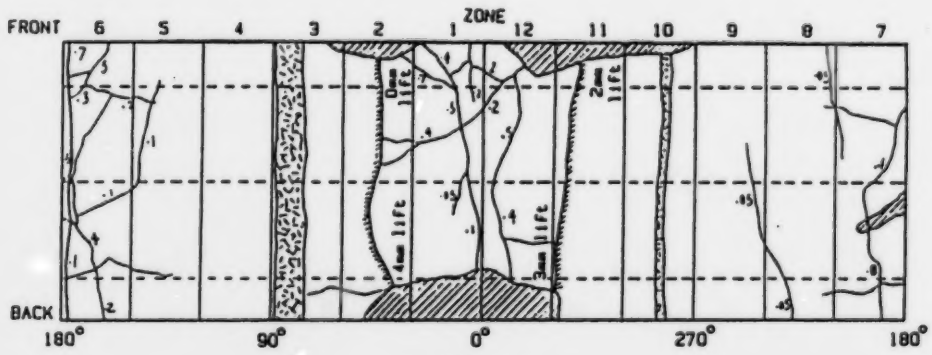
Figure 7
Maximum Ovalling



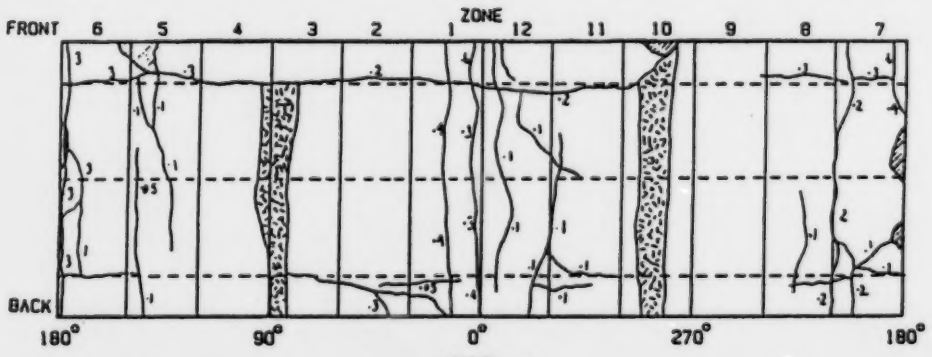
MODEL 1



MODEL 2



MODEL 3



MODEL 4

Note: All dimensions are in millimetres

FIGURE 8
CRACK MAPPINGS OF INSIDE SURFACE

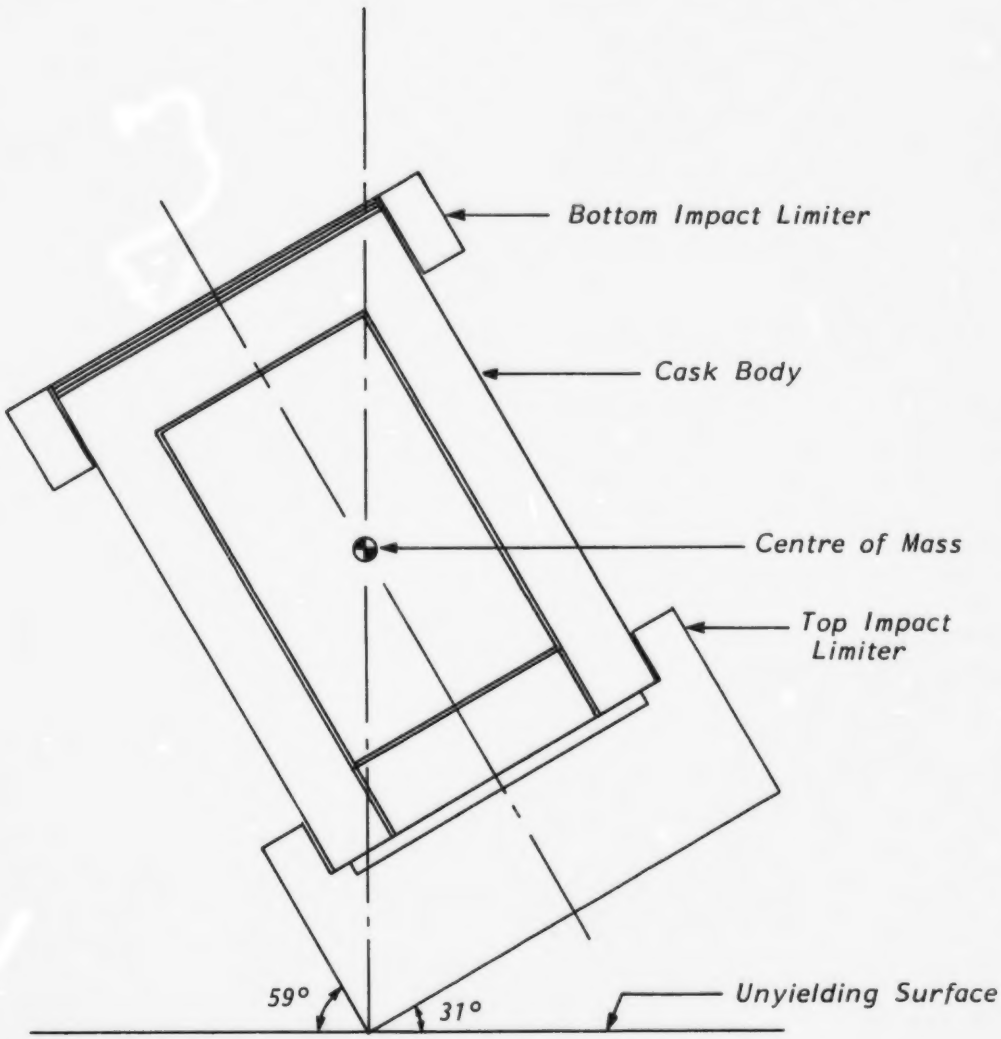


FIGURE 9
DROP ORIENTATION FOR CONTAINED CONCRETE CASK (CCC) SCALE MODELS

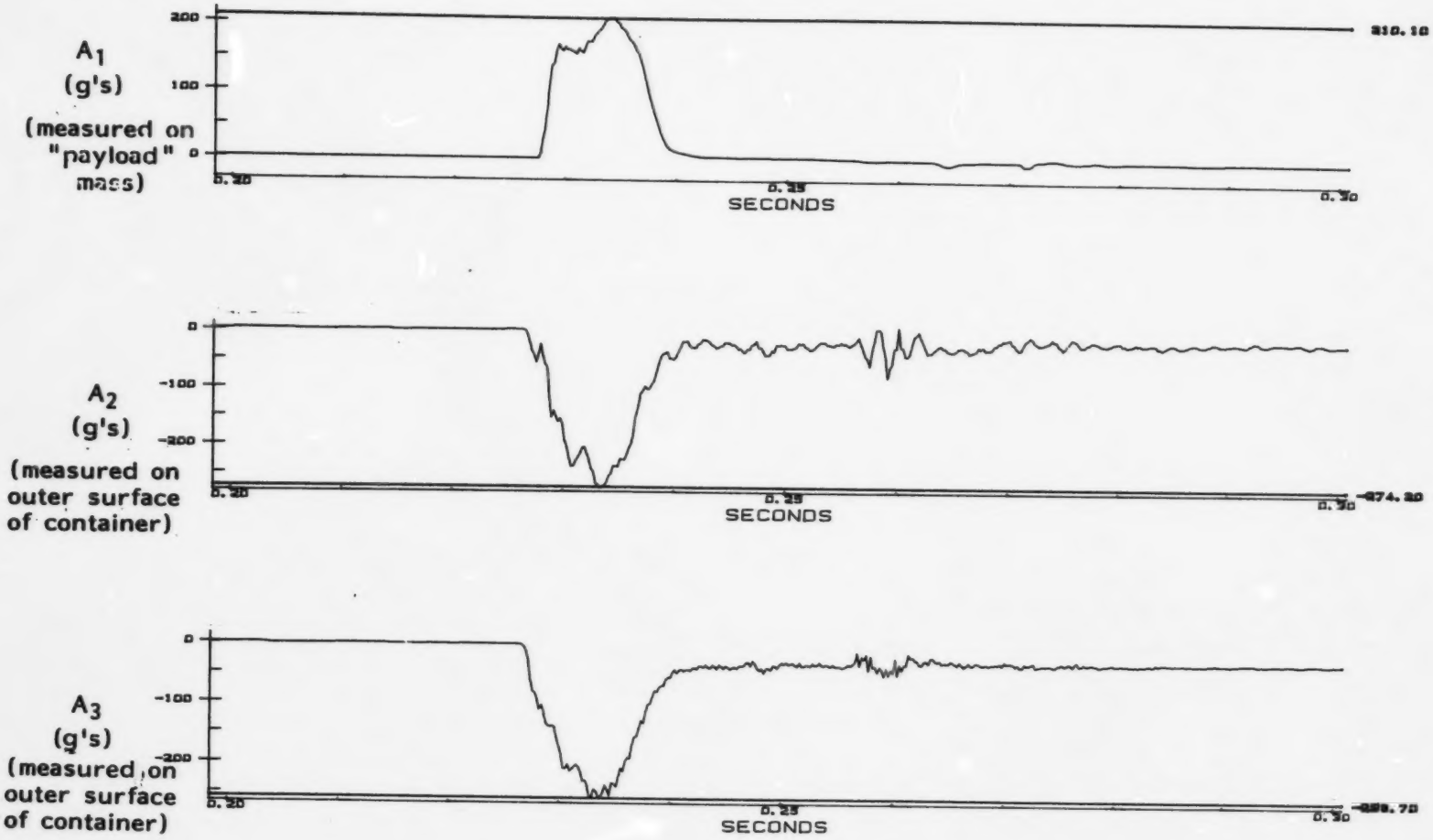


FIGURE 10A

DECELERATION DATA, MODEL B, '1/8' SCALE AT LOCATIONS A_1, A_2 AND A_3

UNITS = g's

(TOP CORNER)

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177216-RD

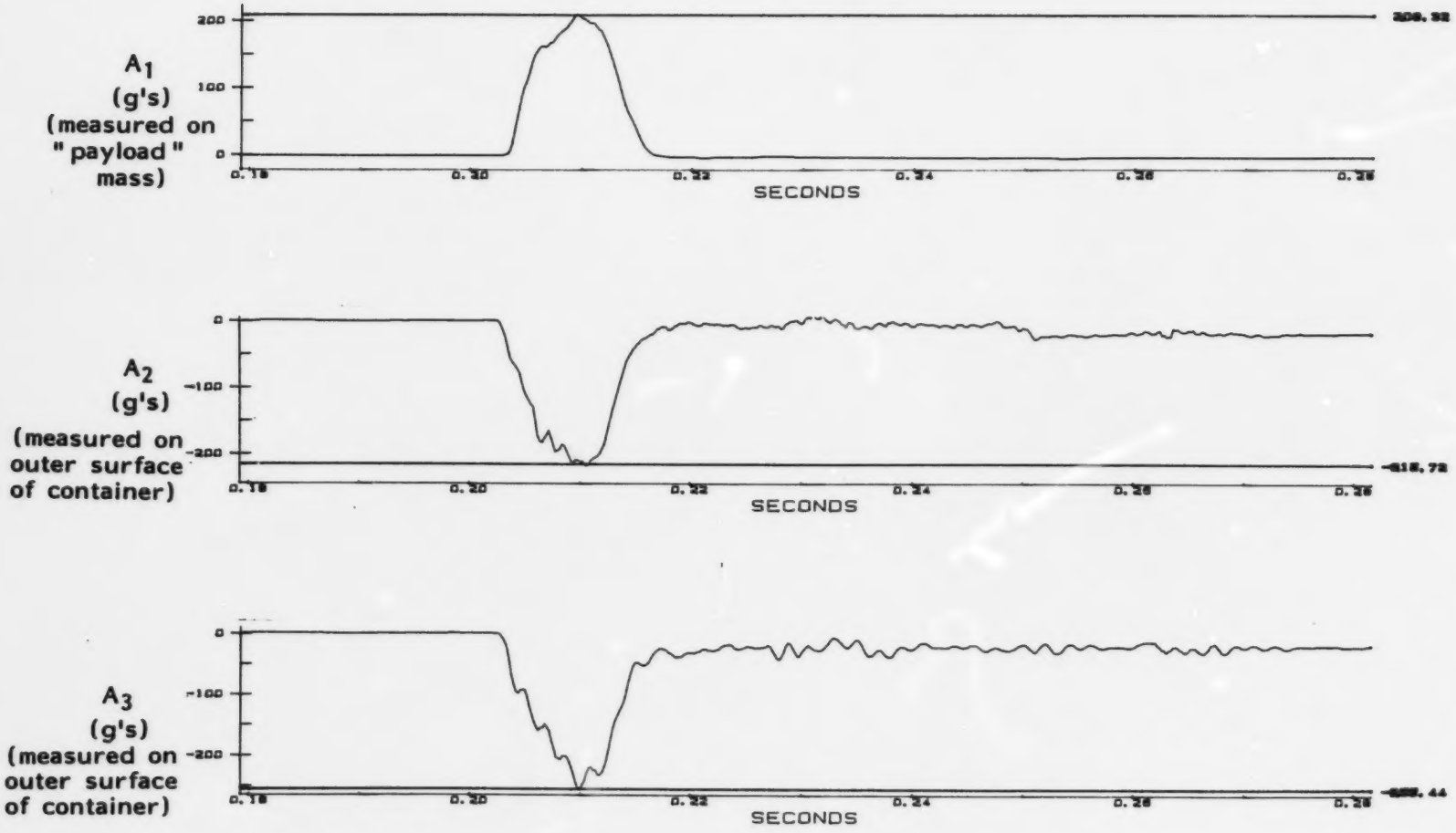

FIGURE 10B

DECELERATION DATA, MODEL A, '1/8' SCALE AT LOCATIONS A_1, A_2 AND A_3

UNITS = g's

(TOP CORNER)

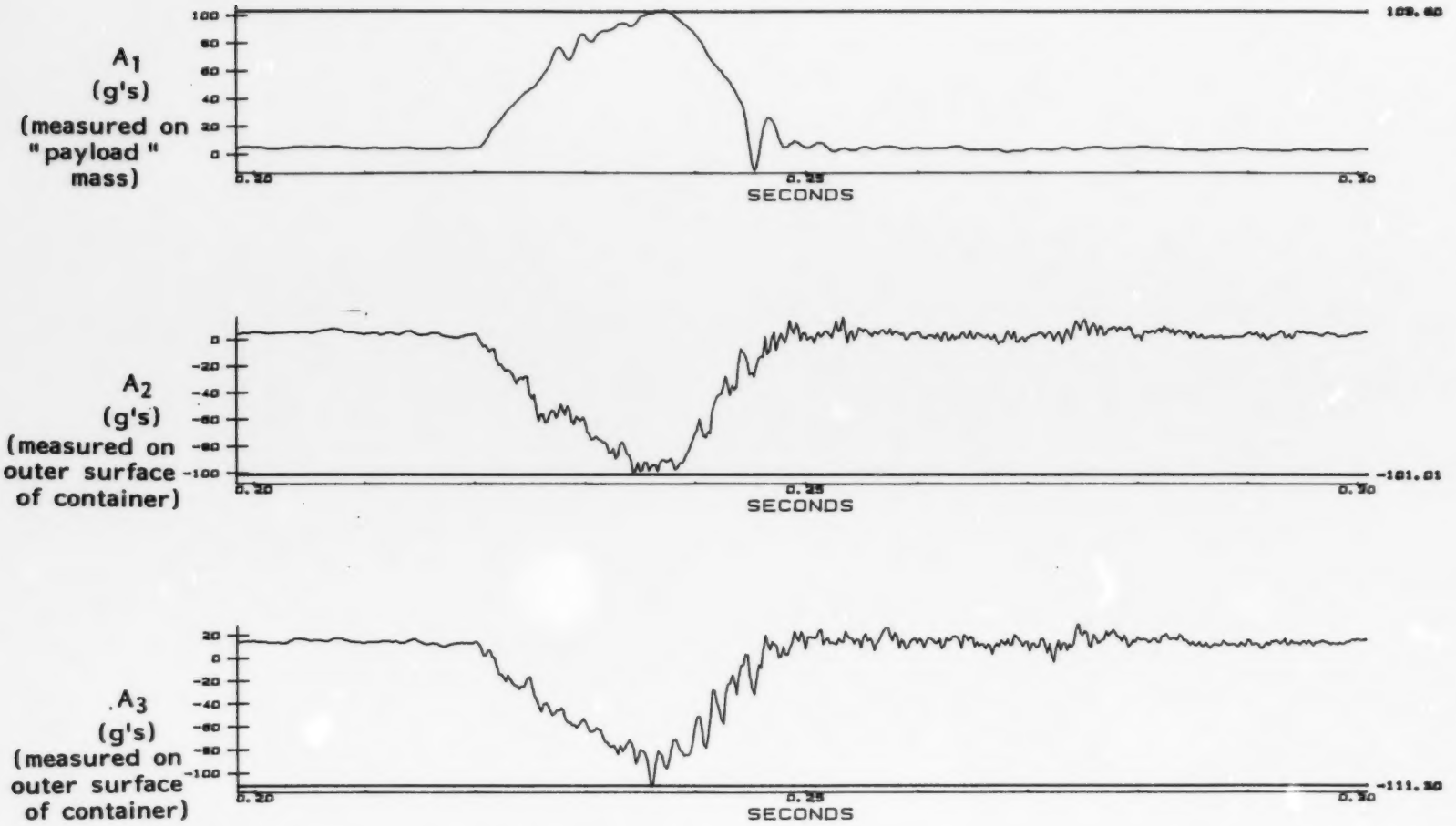

FIGURE 11

DECELERATION DATA, MODEL D, '1/4' SCALE AT LOCATIONS A_1, A_2 AND A_3

UNITS = g's

(TOP CORNER)

FIGURE 12

SCALING OF FOAM FILLED IMPACT LIMITING STRUCTURES

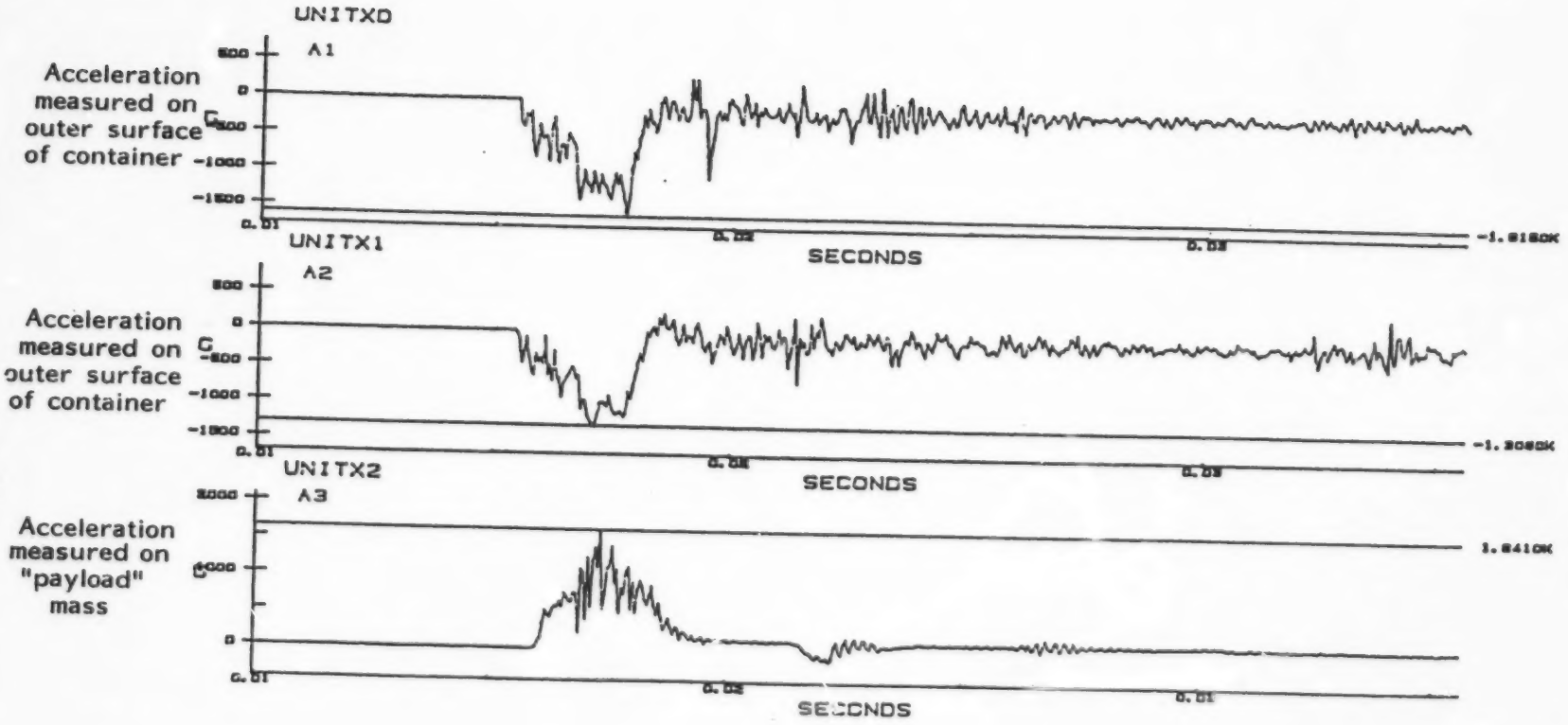

FIGURE 13

ACCELEROMETER DATA FOR MODEL D
(1/8 SCALE MODEL, TOP CORNER DROP)
(UNITS = g's)

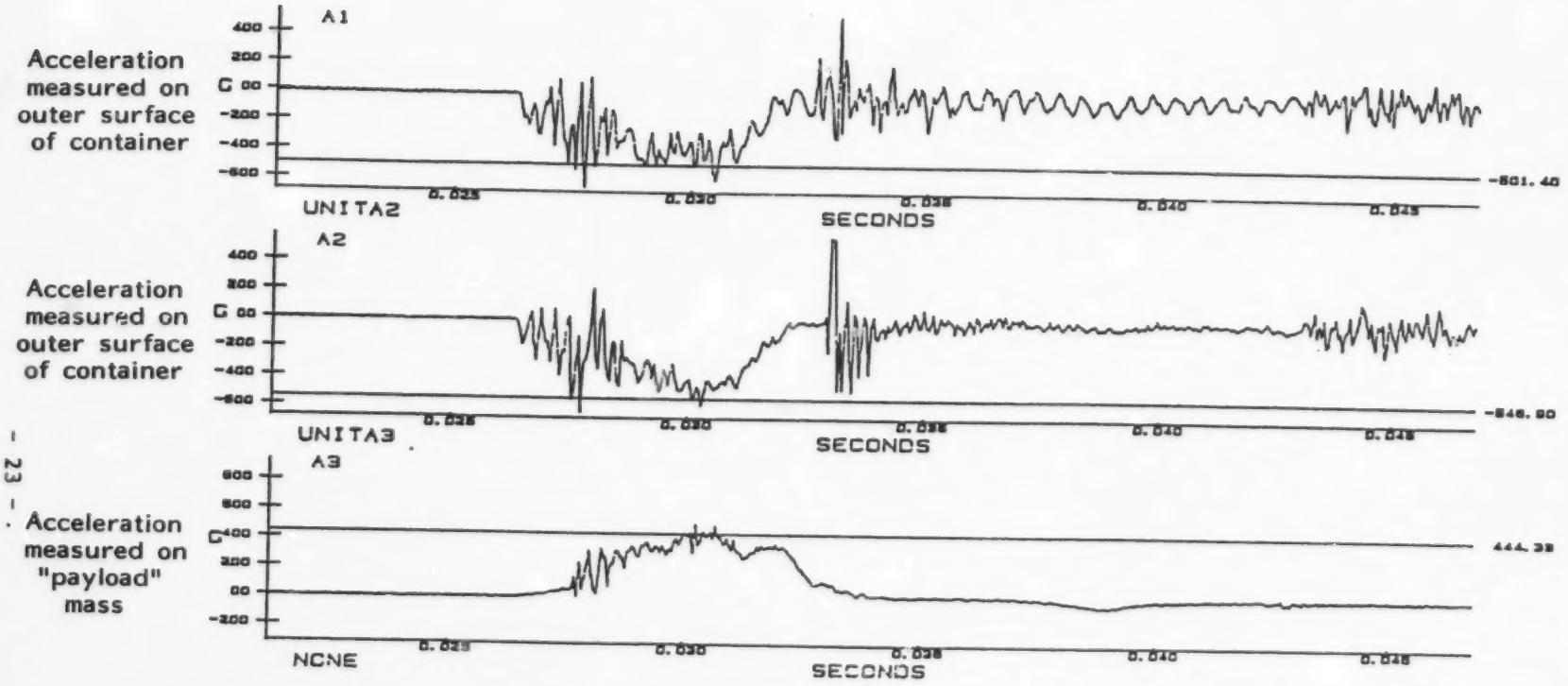

FIGURE 14

ACCELEROMETER DATA FOR MODEL C
(1/4 SCALE MODEL, TOP CORNER DROP)
(UNITS = g's)

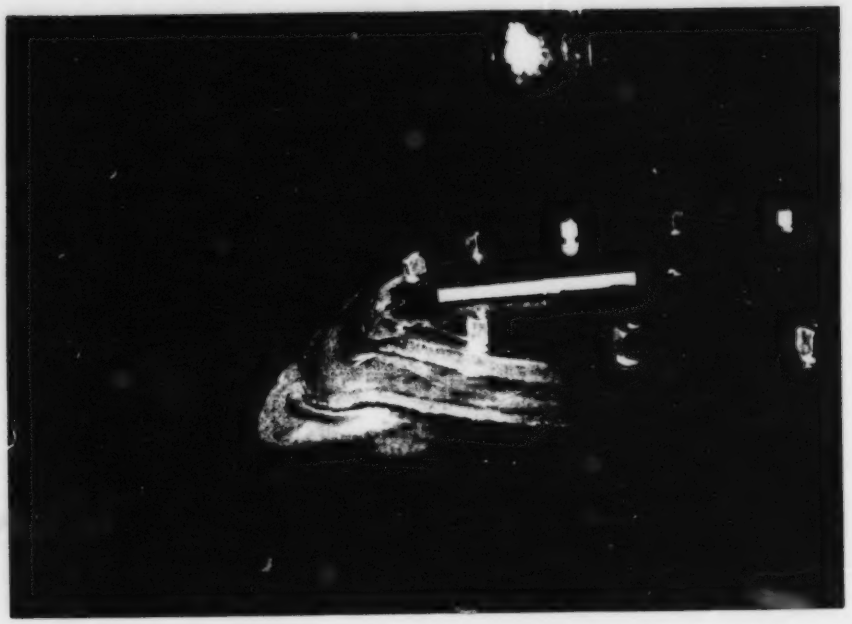

FIGURE 15

EXTENT OF SUPERFICIAL DAMAGE TO 1/4 SCALE (UPPER) AND 1/8 SCALE (LOWER) MODELS FROM 9 METER DROP WITHOUT IMPACT LIMITERS

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BART 6 DISK

88-301

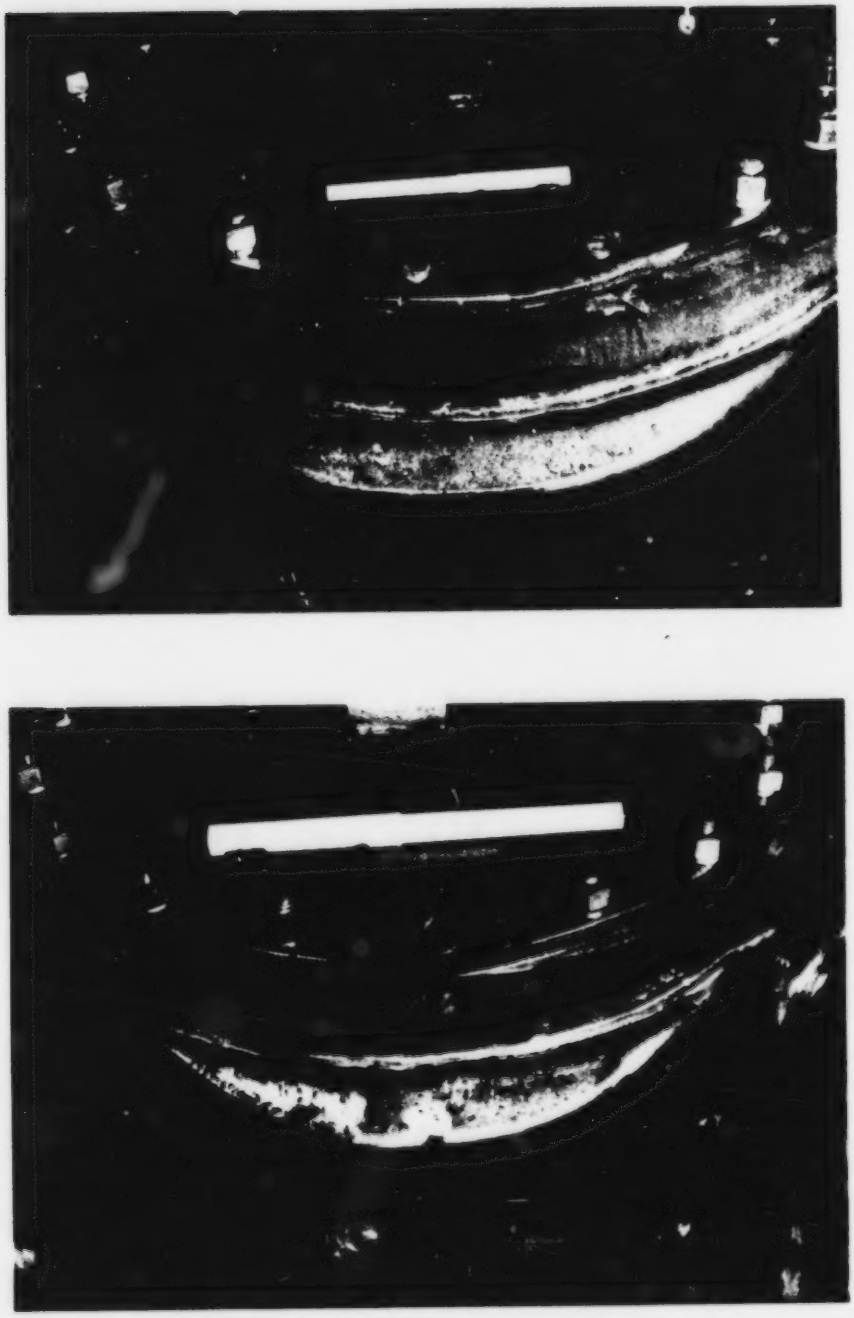

FIGURE 16

EXTENT OF SUPERFICIAL DAMAGE TO 1/4 SCALE (UPPER) AND 1/8 SCALE (LOWER) MODELS FROM 9 METER DROP WITHOUT IMPACT LIMITERS

178743-RD
BART 6 DISK

FIGURE 17

1/8 SCALE TOP CORNER DAMAGE (FACE)

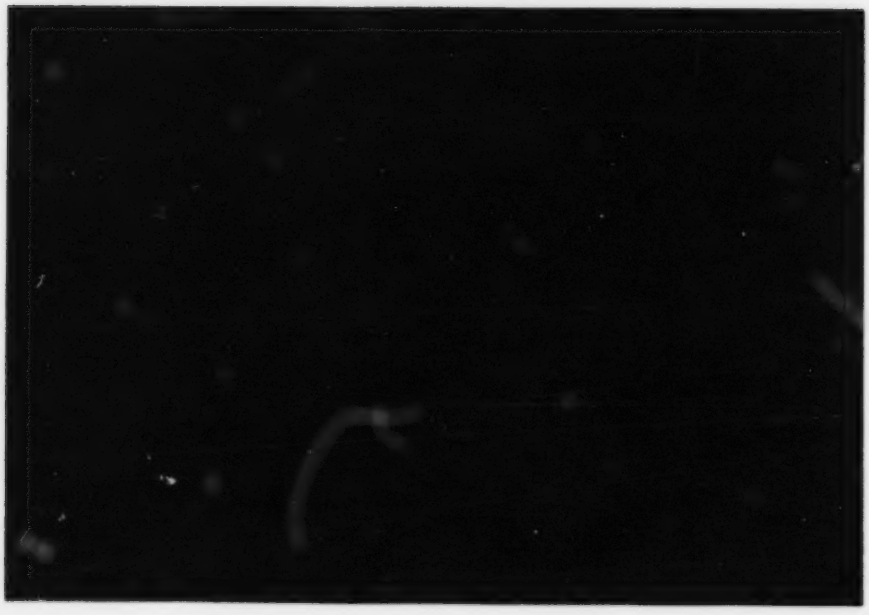

FIGURE 18

1/4 SCALE TOP CORNER DAMAGE (FACE)

FIGURE 19

1/8 SCALE TOP CORNER DAMAGE (END)

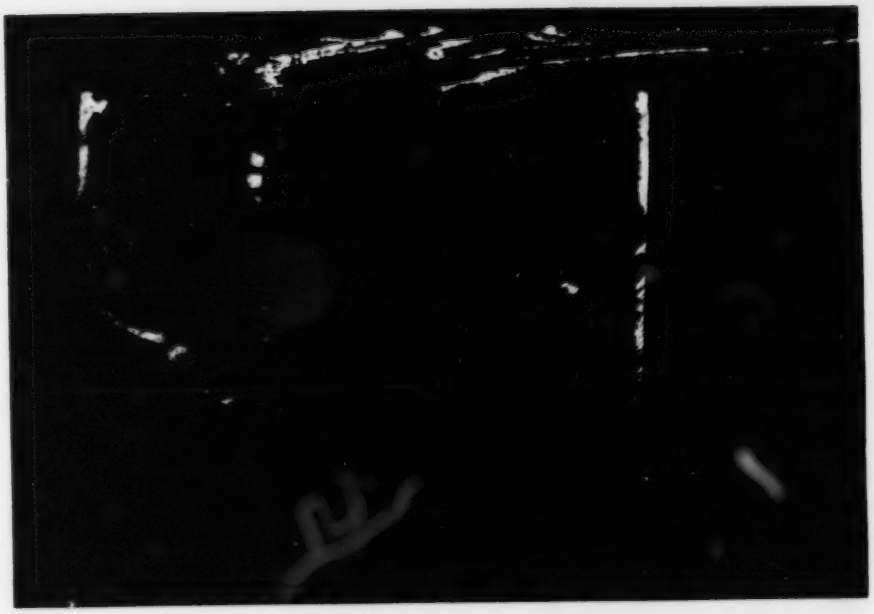

FIGURE 20

1/4 SCALE TOP CORNER DAMAGE (END)

FIGURE 21

1/8 SCALE SIDE DROP

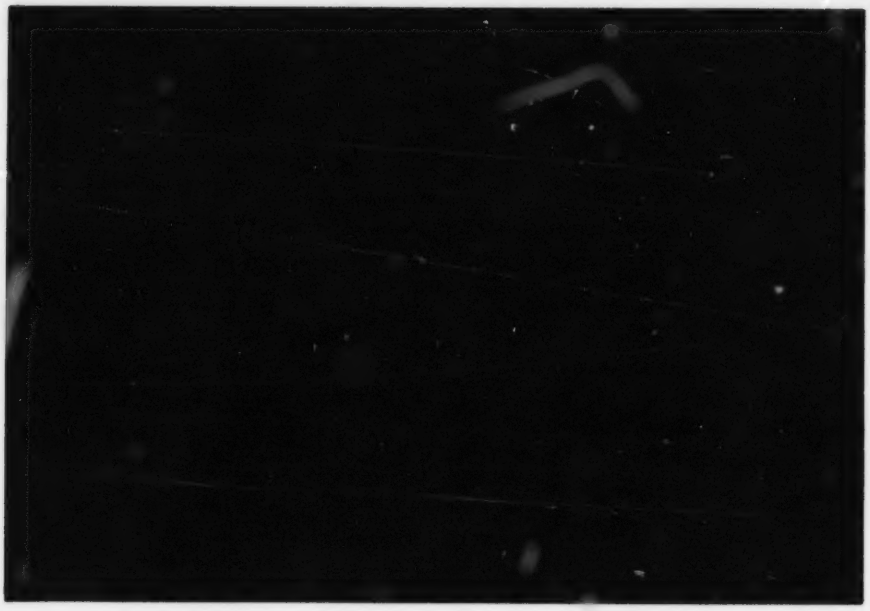

FIGURE 22

1/4 SCALE SIDE DROP